592

VOLUME 81 SEPARATE No. 592

PROCEEDINGS

AMERICAN SOCIETY OF CIVIL ENGINEERS

JANUARY, 1955

SAND FILTRATION STUDIED WITH RADIOTRACERS

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(Discussion open until May 1, 1955)

Headquarters of the Society
33 W. 39th St.
New York 18, N. Y.

PRICE $0.50 PER COPY

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This paper was published at 1745 S. State Street, Ann Arbor, Mich., by the American Society of Civil Engineers. Editorial and General Offices are at 33 West Thirty-ninth Street, New York 18, N. Y.

SAND FILTRATION STUDIED WITH RADIOTRACERS

Donald R. Stanley, M. ASCE[1]

SYNOPSIS

Sufficient fundamental information concerning the mechanisms involved in the removal of suspended particles from water by rapid sand filters has not been available to make possible other than a largely empirical and sometimes wasteful approach to their design. The present study was greatly facilitated by the development of methods and equipment for using radioactive tracers for studying these fundamental processes. Experiments were conducted to investigate several of the more important variables involved in the operation of rapid sand filters. Formulae expressing some of these variables are presented and methods of investigating others suggested. . . . .

INTRODUCTION

Despite the long period of development and the present widespread use of rapid sand filters, little fundamental information concerning the mechanism of their removal of suspended matter has been obtained. Hence in spite of the tremendous investment in plant and equipment, design is primarily based on rules of experience, most of which are applied with too little reference to local conditions. Three of the most important design factors: depth of bed, size of sand grain, and rate of flow, are almost always chosen without reference to factors as important as the character of the particles to be removed and the requisite quality of effluent. Generally it may be said that the state of the art is still such that we know only that plants designed according to presently accepted practice will work satisfactorily. We are, however, ignorant of the magnitude of the safety factors being included to produce present results. Consequently, many plants may be greatly over-designed.

The first substantial effort to identify some of the problems inherent in the removal of suspended matter by rapid sand filtration, was made by a committee of the American Society of Civil Engineers (1) which published a progress report in 1936.

Since that time Eliassen (2), Stein (3), Iwasaki (4), Slade (5), Baylis (6), (7), (8), (9), (10), (11), Hudson (12), and Geyer and Machis (13), have made significant contributions.

Purpose and Scope of Investigations:

The major variables involved in the removal of suspended material by rapid sand filters include; size, uniformity of size, shape, and surface condition of sand grain; porosity and depth of bed; rate of filtration; size, size distribution, concentration and character of particles to be removed and temperature of suspending medium.

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For the most part, since previous investigations have been carried out under plant operating conditions, rigid control of some of the important variables has not been accomplished, and adequate study of them has not been made. The prime purpose of the present investigation has therefore been to evaluate, under controlled laboratory conditions, the effect of certain of the foregoing variables on the penetration of floc into sand filters and to suggest methods of investigating others. In particular quantitative evaluations of the effect of sand size and rate of filtration and consequent formulations have been determined. In a less detailed fashion, evidence has been produced to show that the effect of hydrogen and other ion concentration on the character of the floc, and the age, concentration and size of floc particles, are also important factors in the removal of suspended matter by sand filters. Evidence has also been found to suggest that the condition of the surface of the sand grains could affect the penetration.

Incidental to the main purposes of the investigation, has been the preliminary development of (1) a method of preparing a uniform reproduceable flocculant suspension for testing the performance of the experimental filters; and of (2) a reliable and rapid means for determining the floc concentration at different depths in cylindrical experimental filters.

Development of Experimental Apparatus and Procedures:

Previous investigators have been handicapped by two major difficulties; that of conducting filtration experiments with a suspension of floc that can be readily reproduced and maintained in a uniform condition; and that of determining floc concentration at different depths in the filter by a rapid and reliable method.

The first difficulty was overcome for the purposes of this study by the choice of the common coagulant ferric chloride ($Fe\,Cl_3$), after first testing numerous powders in suspension. Reproduceability was obtained by using distilled and deaerated water with the necessary reagents and homogenizing the floc by passing it through an orifice just prior to filtration. The second difficulty was overcome with the aid of a radioactive isotope, I^{131}. A method of using this isotope as a tracer for ferric oxide floc was developed, and special equipment for determining the concentration of radioactive substances in cylindrical columns, was constructed.

The main experimental data were obtained from the operation of six filters constructed of 1-1/2 in. I.D. Lucite tubing. Filter media consisted of uniform Ottawa sand of different sizes.

Development of Technique for the Use of a Radioactive Isotope, as a Tracer for Hydrous Ferric Oxide Floc.

After considering several isotopes as possible tracers, I^{131} was chosen because it is inexpensive, has a short half-life, and is a good gamma ray emitter. However, its successful use depended on combining it intimately with the ferric floc. This was accomplished by the mutual coagulation between negatively charged, colloidal AgI and positively charged hydrous ferric oxide.

After solving the problem of combining the I^{131} with floc it was then necessary to develop a method of determining the concentration of I^{131} (and thus the iron) at various depths in a sand filter containing the radioactive floc.

This was accomplished by the use of a Gieger tube having a high efficiency in Gamma ray counting, mounted in a specially designed shield. The equipment used for determining the concentration of radioactivity at different

depths in a filter tube is shown in Figure 1. A filter tube with sand in it is shown in place in the counting equipment. A worm gear attached to an electric motor located in the bottom of the stand allows the filter tube assembly to be moved up or down at a uniform velocity in front of the lead counting shield. The high efficiency gamma Geiger tube is shown installed in the lead shield and connected to a 64 Scaler at the right side of Figure 1. Between the Geiger tube and the filter tube there is a 1/4 inch slit through which gamma rays may pass from radioactive material in the filter tube to the Geiger tube and thence be recorded on the 64 Scaler. Thus the counting rate on the Scaler varies directly as the level of radioactivity opposite the 1/4 inch slit in the lead shield.

For operation the filter was placed in front of the shield so that the slit was below the lowest point to be scanned in the filter. The movement of the filter downward was started simultaneously with the operation of the 64 Scaler. While the filter was moving at a constant velocity, records of cumulative times and counts were made. From these figures the concentrations of floc at the various depths in the filter were readily calculated.

The tubes finally selected for the construction of the filters were 1-1/2 in. (inside diameter) Lucite tubes with 1/4 in. wall thickness.

The inlet assembly to the filter tube was designed to be inserted in the tube and made water-tight at any desired elevation. This assembly could then be placed very close to the sand surface, thereby reducing to a minimum the space in which floc could agglomerate before entering the sand. Six filters were constructed. Each was attached to a wood backing, on the face of which were five manometers. These allowed observations to be taken of the head loss to four different depths in the filter.

For the sake of radiological safety, it was decided at the beginning of the experiments to read the manometers with a telescope having a horizontal cross-hair. However, after the first two runs had been made, this method of reading was replaced by a photographic one. Photographs were taken of the filter assemblies and the manometers were read from the developed negatives using a microscope. Except in a few cases in which the miniscus was obscure, the readings were precise to about 0.02 cm of mercury.

Presentation and Discussion of Results

Data on the experiments conducted are presented and discussed below under the following headings: Calculation of Parameters, Variables Investigated, Special Tests, On the Removal Process, and Application to Practical Problems.

Calculation of Parameters

To interpret the experimental results, it was necessary to introduce a number of parameters relating to the concentration of floc in the sand, the depth of penetration of floc and the head loss increase.

Concentration of Floc in Filter Sand:

The concentration of floc at various depths in the filter sand was calculated as mg of Fe per cc of sand. The relative concentration of I^{131} (and thus of Fe) at various depths in the filter bed was easily determined with the counting equipment already described. Knowing the total Fe passed in the filter, its concentration at any depth was readily calculated.

In experiments carried out under the direction of a committee of the American Society of Civil Engineers (1) "penetration" was defined, (a) as that depth in the filter at which a half-inch layer of sand, when stirred in one liter of distilled water, produced a turbidity of 10 ppm, or, (b) the depth of a filter that released 0.02 ppm or more of turbidity to the effluent. Neither definition was suited to the present study. The second obviously identified only the time during a run at which the defined penetration reached the full depth of the filter. The first required the destruction of the filter bed.

A number of ways of defining penetration were considered. That finally chosen involved the use of the Fe distribution curves such as those shown in Figs. 2 and 3. With the special counting equipment used for determining the level of radioactivity at different depths in a filter tube variations in background had a tendency to obscure the zero point (depth of penetration) on the curve. Therefore the penetration was defined as the intersection of the observed Fe distribution curve with the line drawn parallel to the zero Fe concentration line but at a point equivalent to the background count plus one standard deviation of the background count.

Penetration Index:

In order to determine the relationship between penetration and filter loading, the penetration in inches was plotted against the total Fe in mg/sq cm of filter surface for Filters 1, 3, and 5 in Run No. 6, as shown in Figure 4. The points are seen to trace a straight line passing through the origin. Data from Run No. 5, Filter No. 6 are also plotted on the same graph.

Similar graphs for other conditions of flow rate, sand size, concentration of floc, and pH also showed straight-line relationships. Thus it appears that the slope of these lines constitutes a good parameter for the analysis of the experimental results in terms of observed penetration. The resulting parameter was named the "Penetration Index" and is defined as the penetration in cm caused by the passage into a filter of 1 mg of Fe/sq cm of filter area.

Head Loss:

The length of a filter run is generally limited by the head loss. If sufficient head is available, the length of run is limited by the depth of penetration of the floc. When floc reaches the bottom of the filter, the quality of the effluent deteriorates and the filter must be backwashed.

In order to compare the effect on the head loss of the different variables investigated, the increase in head loss was plotted against the total Fe/sq cm of filter area. Such a plot is shown in Figure 5, and indicates a definite linear rise of increase in head loss with applied Fe, but the slopes of the lines differ for each filter. This was probably caused by failure to apply the same concentration of floc to each filter.

The significant observation, however, is the excellent straight line relationship between total Fe and head-loss increase. The middle line appeared to be a good average for the three and was used for comparisons with other runs.

Variables Investigated

During the course of the present study the variables investigated were: size and concentration of Fe floc, hydrogen and other ion concentration in the suspending water, size of sand in the filter and rate of flow of applied water.

An important variable which is of practical significance in plant operation is the water temperature. No attempt was made to determine the effect of temperature changes because considerable equipment modification would have been required. The temperatures of the suspensions used were recorded in each run and did not fall outside the range of 24° to 26° C.

Size of Floc Particles:

No thorough investigation was made of the effect of size of floc particles on penetration. However in Run No. 1, 0.021 in. orifices were used ahead of Filters 1 and 6 while the same suspension was pumped from the gear pumps through 1/4 in. O.D. Saran tubing directly to Filters 2 and 4. Where no orifices were used, the floc particles were visibly much larger. The penetration recorded was at least three inches less than that observed in Filters 1 and 6, and a much thicker layer of floc settled on top of the sand.

The only conclusion that can be drawn from Run No. 1, is that the size of floc particles affects the penetration. No study was made on the effect of changing the orifice size although this would have varied the particle size and probably, therefore, the penetration. The orifices provided a homogenizing action that not only made particles about the same size as those from sedimentation tank effluent but, more importantly did this in a reproduceable way.

Eliassen (2) measured particle sizes on samples taken from different depths of an experimental filter operating on effluent from a sedimentation basin of a municipal water treatment plant. He found particles from 20 microns in diameter down to colloidal sizes but measured only those greater than 6 microns in diameter. The results showed constantly smal'er particles at greater depths.

Concentration of Fe:

Geyer and Machis (13) used alum floc suspensions in concentrations varying from 10 to 60 ppm. They reported that for a given total alum loading of a filter, concentration was not a significant variable. Consequently, they were able to reduce the times of their filter runs by increasing the influent concentrations. To substantiate these findings, three different concentrations of Fe were applied to filters: 3.41, 10.18, and 27.2 ppm (Run No. 3). The results showed that penetration increased significantly with concentrations for the same total Fe passed into the filter.

The penetration index was calculated for each concentration and plotted against the concentration in Figure 6. The straight line shown was drawn by eye and most of the weight was given to the data from Run No. 3. The equation of this line is:

$$PI = 0.62 - 0.065\ C.$$

where PI is the Penetration Index in cm/mg/sq cm and C is the concentration of Fe in ppm.

The reason for this effect is probably that the floc produced at higher concentrations is less dense. Precipitation from homogeneous solution (14) as used in analytical chemistry illustrates how a reduction in concentration (or slowing down the reaction-rate) causes a much denser precipitate to form. The rapid formation of floc at high concentration causes a larger percentage of water to be included in the precipitate. The attractive forces would be weaker for the less dense floc, allowing it to penetrate deeper into the filter.

With aging, the floc has a tendency gradually to exclude water and to become denser (15). Both the floc in the highly concentrated suspensions, and that in the more dilute ones, may approach the same density if they are aged sufficiently.

pH Value:

The hydrogen-ion concentration greatly affects the mechanism of coagulation. For the same reason, it has been reported (10) to affect the filterability of a floc suspension.

The pH of the standard suspensions (6.87 ppm Fe) was about 6.8. In experiments to determine the pH effect, its value was adjusted with 0.6N HC1 or 0.5N NaOH. In Run No. 5, the pH of the suspension for Filter No. 4 was adjusted to a value of 5.2. Samples of the effluent, taken just before the filter was removed to determine the distribution of Fe showed that 39% of the floc was passing through the sand. Observations of the suspensions showed that the particles became smaller when the pH was lowered to 5.2 from its normal value of about 6.8.

An H ion is a specific counter ion which neutralizes hydroxyl groups on hydrous ferric oxide floc. This high affinity for the floc produces positively charged particles when sufficient H ions are present. When particles are broken up in the presence of a large number of H ions, they will not coagulate again as readily, because the resulting high positive charge causes an increase in the electro-kinetic repelling forces.

This reasoning may also be used in explaining why a large percentage of such floc passes through a sand filter. Clean Ottawa sand grains have negatively charged surfaces. Thus, it would seem that positively charged particles in suspension would be readily removed. This is probably true so long as the surface of the filter medium remains negatively charged. However, the small particles in suspension coat the sand grain surfaces very rapidly, producing a charge essentially the same as that on the floc particles in the suspension. The particles would then have the best chance of adhering to one of these surfaces if the electro-kinetic repelling forces were at a minimum. This occurs at pH values close to the isoelectric point. Thus, the best coagulating floc would probably also be the best filtering floc.

The Penetration Index for different pH values was plotted against the pH in Figure 7, and a curve very similar to the familiar "time of floc formation versus pH curve" was obtained. The minimum value seemed to lie at a pH of about 7.0, whereas with the "time of floc formation versus pH curve" the minimum point (time of most rapid floc formation) lies at a pH of about 6.0. It is possible that this shift is due to experimental error.

Ion Concentration:

In the preceding section, the effect of H ion concentration has been discussed. Other ions in solution were expected to have similar effects. In order to investigate them, three standard suspensions containing, respectively, 500 ppm of NaCl, Na_2SO_4, and $MgSO_4$, were applied to three filters. It was observed that the $MgSO_4$ and Na_2SO_4 increased the Penetration Index by 65% to 70%, whereas the NaCl increased it by only about 15%.

Size of Sand:

To determine the effect of sand size on penetration, five different sizes of Ottawa sand were used in six filters. The Penetration Index was determined

for each size of sand and plotted in Figure 8 against the sand size as determined by different methods. For the curve, which is plotted with the geometric mean sand sizes by weight as determined by the Fair-Hatch method, a good fit is obtained by a straight line passing through the origin. The best-fitting straight line for the curve which is plotted with geometric mean sand sizes by the manufacturer's rating has an intercept at a Penetration Index of 0.12 cm/mg/sq cm. The equation of the curve may be represented as:

$$P.I. = 0.12 - 1.27\ d$$

where P.I. is the Penetration Index in cm/mg/sq cm and d is the sand size by geometric mean of the manufacturer's rating in mm.

The sand sizes used for plotting the lower curve were obtained from actual measurements while those for the upper curve were derived from the nominal sizes of the openings in the sieves used for classifying the sand.

Rate of Flow:

The effect of rate of flow was investigated in Run No. 8. Rates of 1.0, 2.0, 4.0, and 5.25 gpm/sq ft. were passed through filters of 20-30 mesh sand, and rates equivalent to 1.0 and 2.62 gpm/sq ft. were passed through 40-50 mesh sand.

The penetration was plotted against total Fe. Except for the flow of 2.62 gpm/sq ft with 40-50 mesh sand, the points obtained did not lie on a straight line passing through the origin. Instead, straight lines fitting the points had positive penetration intercepts. The Penetration Index was therefore computed by two methods: (1) the slope of the line between the origin and the centre of gravity of the points available, and (2) the slope of the best fitting line ignoring the origin.

The Penetration Index obtained by both these methods was plotted against the flow rate in Figure 9. Straight-line relationships passing through the origin were indicated in each case. Points obtained in Runs 6 and 7 were also plotted and agreed more closely with the Penetration Index computed by the first method described in the preceding paragraph, and the equation of the resulting straight line shown in Figure 9 (for 20-30 mesh sand) is:

$$P.I. = 0.48\ Q$$

where P.I. is the Penetration Index in cm/mg/sq cm and Q is the rate of flow in gpm/sq. ft.

Special Tests

The equipment and methods developed in the present study provided an excellent tool that has hitherto not been available for investigations of this nature. Consequently it was possible to conduct several special tests which supplied helpful information concerning the fundamental mechanisms involved in the removal process.

Radioactive Suspension Followed by Non-Radioactive Suspension:

One of the special tests involved operating a filter for 151 minutes, using a standard suspension containing 6.87 ppm Fe and then for an additional 135 minutes, using a similar suspension but containing no I^{131}.

The total net count and the distribution of this count was practically identical after each interval of filter operation. This indicates that, during the

interval of operation with non-radioactive suspension, none of the floc deposited in the previous period of operation was dislodged and washed deeper into the filter. It has been widely assumed that shearing of deposited floc and subsequent deposition at greater depths in the filter accounted for much of the penetration.

Distilled Water Passed Through Filter After Run with Standard Suspension:

After operating a Filter for 420 min. with standard suspension, distilled water containing 50 ppm NaCl was passed through it for 105 mins. Following this, a suspension with AgI sol. including I^{131}, in the same concentrations as in a standard suspension (but with no Fe), was pumped through the filter for 75 min. Distribution of I^{131} with depth was determined at 210, 420, 525, and 600 min.

The total net count and the shape of the distribution curve before and after the distilled water was used, were identical for all practical purposes. This proves that I^{131} is not removed from the floc by water flowing through the filter. It also lends further support to the conclusions of the foregoing section with respect to the movement of deposited floc to greater depths in a filter.

The very fine particles of AgI sol. are readily removed in a filter containing iron floc. Most of this removal was found to occur in the top 1-in. of sand but extended as deep as 3-in., although the penetration of floc was as much as 8-in. A clean sand filter (negatively charged sand surface) probably would not remove an appreciable percentage of negatively charged AgI sol.

High Flow Rate Followed by Lower Flow Rate:

After Filter No. 3 in Run No. 8 had been operated for 210 min. at 4.0 gpm/sq ft., it was continued in operation for an additional 171 min. at 2.0 gpm. sq ft. During this latter interval, an additional load of Fe amounting to 41% of that applied during the first 210 min. of operation was added to the filter. Only a negligible increase in penetration was observed.

These results indicate that the practice of operating filters at constant flow rates throughout the duration of a run should by no means be considered sacred. It appears that it would be safer to operate filters at high rates at the beginning of a run when there is little penetration than near the end when penetration is deeper. Also, the necessary head is available to obtain a higher rate at the beginning of a run.

The present trend is to design filters for higher rates than 2.0 gpm/sq ft. The hydraulic design of many existing plants, however, does not allow much increase in rate of flow if the rate is to be kept constant throughout the run, unless the duration of the run is considerably reduced. It would be possible to obtain a high rate when the sand is clean and to reduce it as head loss is increased. When the head loss in the sand is increased sufficiently, the rate controllers will not govern, and the rate of flow will begin to decline as the filter clogs. Baylis (11) has reported operating filters successfully in this way at Chicago, when the hydraulics of the plant did not permit sustaining some of the high experimental rates being used.

On the Removal Process

Many mechanisms have been suggested as governing the removal of suspended floc particles in a sand filter. These include straining, and straining augmented by flocculation, sedimentation, inertia, chance contact with a

surface, and electro-kinetic force. Along with these, two other factors are discussed here, Brownian movement, and van der Waals forces.

Straining:

This is relatively unimportant except possibly for large floc particles which should not be present in the effluent from a well-designed and well-operated sedimentation basin. The report of the American Society of Civil Engineers (1) describes the importance of flocculation within the filter bed, the contention being that the larger particles thus formed are strained out. The present study indicates that the presence of a large surface area of floc which is attached to sand surfaces will promote absorption of small floc particles on this surface. In this sense, it may be called coagulation.

An analysis of the conditions in a filter bed of 20-30 mesh sand through which water is passing at the rate of 2 g.p.m./sq. ft. indicates that the mean velocity gradient is approximately 40 ft./sec./ft. According to Camp and Stein (16), these are optimum conditions for flocculation.

Other factors such as concentration and character of the surfaces of suspended particles are also important. In practice, where there is proper pretreatment, flocculation and sedimentation remove a high percentage of the suspended matter. The suspension finally reaching the filters is of low concentration with fine particles that do not coagulate and settle in the pretreatment chambers. In the filters, essentially all the remaining suspended matter is removed in the top one inch of the bed (when the filter is clean). The retention period in this one inch of depth would be about 20 sec. With the low concentration of suspended matter and the extremely short retention period, it is felt that, in practice, coagulation within the pores of a sand filter would not be sufficient to increase the size of particles to the extent necessary for straining.

In the present study, the concentrations of floc in the suspensions used were in the order of ten times that encountered in practice (sedimentation tank effluent). Despite this, it is felt that the extremely short retention period within the top one inch of a filter would rule out straining due to coagulation in the pores.

Sedimentation:

Stein (3) has concluded that sedimentation of suspended floc particles, within a filter bed, is not an important mechanism of removal. His conclusion was reached on the basis of microscopic observations on a small filter cell. The filter medium used in this cell consisted of cylindrical lucite rods mounted at right angles to the direction of the flow. A series of photomicrographs showed the progressive build up of floc on the surface of the rods as the floc was removed from the suspension being filtered. The floc particles appeared to adhere mostly at points where the cylinders were closest together and did not seem to have any preference for horizontal surfaces. From these observations, Stein developed his contact-action theory and ruled out sedimentation. He also argued that particles too small to be removed in a sedimentation tank are not likely to settle out in a sand filter.

A method used by Hazen (17) for slow sand filters has been employed by Fair (18) to show that a sand filter 1-meter deep and composed of sand of diameter 0.5 mm, would be expected to remove, by settling, particles 1/20 of the diameter of particles removed in settling basins. In arriving at this figure, only 1/18 of the total sand grain surface area is assumed to be available for sedimentation. This being a conservative estimate, it would seem that the

"sedimentation theory" cannot be completely ruled out as Stein suggests.

Inertia:

An analysis of conditions during the operation of a rapid sand filter, indicates that the forces due to inertia are in the order of 1% of the magnitude of those due to gravity. Also, if inertia were the principal force causing suspended particles to cross streamlines to sand grain surfaces, an increase in the rate of filtration would be expected to result in a decrease in the penetration of floc whereas the converse is true. It has been concluded that inertia is not of importance as a removal mechanism.

Chance Contact with a Surface:

Stein (3) has claimed that the removal of suspended matters that are smaller than the constriction in the passageways is accomplished by contact action. He developed equations for an idealized contact mechanism based on the convergence of streamlines at a constriction of a tube. He concluded that the probability of removal of a particle in a unit depth varies directly as the square of the diameter of the suspended matter and inversely as the cube of the diameter of the sand grains. Thus, it is evident that accurate data on floc-particle size would be required in order to evaluate the relative importance of this mechanism.

Electro-kinetic Force:

The importance of electro-kinetic forces in the removal of suspended matter from water by rapid sand filters has been discussed in the section above dealing with the effect of hydrogen-ion concentration on the filtration process.

Brownian Movement:

The importance of Brownian Movement in causing particles in suspension to migrate to a sand surface while water is passing through a filter was assessed by applying Einstein's formula (19) for horizontal displacement of a particle by Brownian Movement. The conclusion drawn was that it is unimportant as a removal mechanism.

van der Waals Forces:

These are attracting forces and will cause coagulation of particles of like charge. With such particles, the electro-kinetic forces between them repel, but when these forces are reduced sufficiently, they are overcome by van der Waals forces, and coagulation results.

Application to Practical Problems

Comparisons with Plant-Scale Results for Length of Filter Run:

Experimental results obtained from cylindrical glass tube filters have been established as being indicative of plant-scale operation (1), (12), (20). However, in this investigation, the suspensions used were prepared under different conditions than those encountered in practice. It is therefore considered advisable to compare the experimental results with those obtained in full-scale plant operation.

Baylis (7) (8) (9) (10) and Hudson (12) have reported that the length of filter run varies as (effective size of sand)$^{2.15}$ (initial porosity)$^{3.0}$ and (rate of filtration)$^{1.35}$. Runs were terminated when the head loss increased to 8 ft. Baylis (11) has reported the effect of flow rate on filter efficiency defining the latter as (gal)/sq ft/ (ft rise in head loss). Of these four parameters, all but porosity may be compared with the results of the present study.

Size of Sand:

In order to determine the relationship between sand size and length of filter run, the total Fe at an increase-in-head-loss of 8 ft. (18 in of Hg) was obtained for each size of sand. It was then plotted on double logarithmic paper as shown in Figure 10. Also on the same graph was plotted the total Fe to 8 ft. of head loss for the different sizes of this sand. For the latter plot, there is no point for the 0.175 sand size (70-100 mesh) because the head loss was almost 8 ft. before any Fe was passed onto it. The sand sizes used were the geometric mean of the manufacturer's rating, whereas the relationship presented in the preceding section expresses the size of sand in terms of the effective size.

Statistical analyses of these data indicate that there is no reason to believe that the author's results differ significantly from plant scale operations.

It is believed that the data reported by Baylis and Hudson are based on total head loss. Therefore, the relationship based on a total head loss of 8 ft. is more comparable although an error may have been introduced if the comparisons are for sand beds of different depths. For small sand sizes, such a difference would be important, because the clean-sand-head-loss would be a large percentage of the final 8-ft. loss. The head losses recorded for the experimental filters were for a bed depth of 17 3/4 in.

Rate of Filtration:

Figure 11 shows double logarithmic plots of the relative operating times of a filter against the flow-rate. The relative time in one case was determined for an 8-ft. head loss and in the other for an increase in head loss of 8 ft. The regression coefficients were - 0.531 and - 0.606 respectively. Both are significantly different than the exponent of -1.5 referred to previously. The slope of the line representing this latter exponent is also drawn in Figure 11.

It should be remembered that the depth of sand bed affects the length of run to a fixed head loss. In the author's experiments the depth was 17 3/4 in. The data reported by Baylis are for 24-in. beds. If a correction were made for this added depth, the regression coefficient would increase in magnitude slightly, but it would still be significantly different from - 1.5.

Another explanation for the disagreement may be the effect of sand size. If the total iron (or time) is observed for a head loss of 8 ft., then as the size of the sand becomes smaller, the greater will become the magnitude of the regression coefficient. Thus, the value of - 1.5 would apply only to the size of sand used to determine it. On the other hand, if the length of run to 8-ft. increase-in head-loss were expressed in terms of the flow rate, the exponent might be found to be independent of the sand size.

In the following section, it is shown that Baylis' data on filter efficiency agree with the author's. The filter efficiency was calculated on the basis of increase in head loss and may be recomputed for plottings such as are shown in Figure 12.

Filter Efficiency:

Baylis (10) has presented data on filter efficiency at different flow rates obtained from plant-size filters. This efficiency was defined as the gallons of water passed through the filter per sq. ft. of filter area per foot increase in head loss. Apparently the time rate of increase of head loss was substantially constant. Some of these data are plotted in Figure 12.

For comparison with the author's results, total Fe at 8-ft. increase-in-head-loss for the different flow rates of Run No. 8 are also plotted in Figure 12. Total Fe was chosen as the ordinate but it could readily have been changed to gal/sq.ft./ft. rise in head loss, and plotted on the same scale as Baylis' data. Because of the relatively high concentration of Fe, however, such a plot would have been inadequate. The scale for total Fe was adjusted so that the two lines were close together. The parallel lines then show good agreement with Baylis' data. The regression coefficient for the author's data is 4.56. Its 95% confidence limits are 1.98 and 7.14 and its 50% confidence limits 4.07 and 5.05. For an increase in flow rate from 2.0 gpm/sq.ft. to 4.0 gpm/sq.ft., Baylis' data show an increase in efficiency of 39.5% compared to 48.2% for the author's data. The 95% confidence limits of this latter figure are 18.7% and 90%.

From the above statistics, there is no reason to believe that the author's results are significantly different from those presented by Baylis.

The Problem of Filter Depth:

The depth of a filter bed should be such that effluent of satisfactory quality is produced at all times during a filter run. Baylis (10) (11) has reported that the quality of filter effluent deteriorates slightly with an increase in flow rate but that even with rates as high as 5.0 gpm/sq.ft., the percentage of turbidity passing is insignificant. Fe-determinations made on filter effluent of Runs 1 to 6 inclusive indicate that there is no measurable increase in Fe passing through a filter during the progress of a run until the floc penetrates to the bottom of the bed. Thus, in order to assure a satisfactory quality of effluent, the sand bed must be deeper than the penetration at the end of the run. The proper depth of bed, then, might be determined from the penetration at the desired increase of head loss plus a factor of safety. Allan (20) arbitrarily chose a factor of safety of 25% to be added to his calculated penetration. A rational approach to the choice of a factor of safety should be based on the variances of the factors which determine penetration but such data are not presently available.

Two types of filters may be considered in determining the proper depth: a bed of uniform sand, and a bed composed of layers of uniform sand of different sizes. Only the first will be considered here.

The total Fe applied to a filter at a head loss increase of 8 ft. was obtained for various sand sizes and rates of flow. The penetration in inches corresponding to each of these values of total Fe were determined by multiplying the values for total Fe by the Penetration Index obtained from either Figure 8 or Figure 9.

Penetration data were plotted in two ways on double logarithmic paper; penetration against sand size at a constant rate of flow of 2.0 gpm/sq.ft., and penetration against rate of flow with a fixed sand size of 0.700 mm. In each case, the points traced straight lines. Therefore, it appeared that the logarithm of the penetration p, could be expressed in terms of the logarithms of the sand size d, and flow Q, by an equation of a plane. In order to utilize all the available data, a least-squares regression-plane was fitted to the 11 points expressed in terms of the logarithms of their corrdinates. The equation for this least-squares re-

gression-plane is:

$$\log p - 2.46 \log d - 1.56 \log Q - 0.806 = 0,$$

where p is in inches, d is sand size as determined by the geometric mean of the manufacturer's rating in mm, and Q is the rate of flow in gpm/sq.ft. The above equation may be expressed as $p = 6.4\, d^{2.46}\, Q^{1.56}$.

A graphical representation of the data is shown in Figure 13. To establish the required filter depth, the penetration is determined from equation preceding or from Figure 13 and a factor of safety applied.

CONCLUSIONS AND FUTURE WORK

Conclusions

The following conclusions may be drawn from the results obtained in the experiments.

1. Radioactive iodide, I^{131}, can be used satisfactorily as a tracer for hydrous ferric oxide floc that is being removed from water by filtration through a bed of sand.
2. Satisfactory equipment can be designed and built for the determination of the concentration of gamma radioactivity in a cylindrical column of sand containing radioactive iodine, I^{131}, absorbed in the Fe floc.
3. The depth of penetration of floc into sand filters varies directly as the total load of suspended matter applied per unit area of filter.
4. The Penetration Index increases with floc concentration, decreases with floc aging, and decreases with an increase in floc-particle size.
5. The Penetration Index varies with hydrogen ion concentration and is at a minimum at a pH of about 7.0.
6. The Penetration Index is increased by NaCl, Na_2SO_4, and $MgSO_4$ in solution.
7. The Penetration Index varies linearly with the sand size.
8. The Penetration Index varies directly as the flow rate.
9. Head loss increase varies approximately directly, or shows a slight tendency to exponential increase, with total Fe/sq. cm.
10. The relationship between length of run to 8 ft. of head loss, and the sand size, is in accord with results obtained in full-scale plant operations.
11. The observed variation in filter efficiency with flow rate is substantially the same as that obtained in full-scale plant operations.
12. When suspended matter is removed from water by a sand filter, it remains in place during subsequent filtration, and further penetration is caused by more recently applied matter being carried to greater depths in the filter.
13. Penetration varies as $(\text{sand size})^{2.46}$ and $(\text{rate of flow})^{1.56}$ for the experimental conditions of the present study.

Future Work

A broad range of variables has been investigated in this project and the results have indicated the need for future work, both in support of data already obtained, and in broadening its field of application. The following are brief descriptions of some of the experiments which would aid in the accomplishment of these purposes.

1. I^{131} as a Tracer for Hydrous Ferric Oxide Floc:

Tests conducted in connection with the development of the tracer technique indicated that the percentage of AgI sol particles combining with floc depends

on stirring time. It would also probably depend on the concentration of floc in the suspension. It is recommended that these variables be more carefully investigated. At low concentrations of floc, it might be found necessary to provide at least a one or two-hour stirring time before suspensions are used, in order to assure that a sufficiently high percentage of the AgI sol particles are combined with the floc. A final test of the validity of the method developed could be accomplished by the use of Fe^{59}, in the form of $FeCl_3$. Such $FeCl_3$, used with the regular $FeCl_3$ coagulant, would be an ideal tracer. If two filters were operated under identical conditions, except that in one the suspension was traced with Fe^{59}, and in the other with I^{131}, identical curves, showing the distribution of radioactivity with the filter depth, would indicate a perfect tracing of hydrous ferric oxide floc by use of the I^{131} method, described herein.

2. Size of Floc Particles:

Knowledge of the size of floc particles would be valuable for further interpretation of the data and for evaluating the different mechanisms involved in the removal process. Particle size could be varied by changing orifice sizes. Determination of the size and size distribution of floc particles poses a difficult problem. It is suggested that three methods of microscopic measurements be investigated, namely: ultra microscope, ultra-violet microscope, and blue light illumination. An indirect but less arduous method might be developed by the use of a nephelometer. Such an instrument would have to be calibrated by a direct means of size determination such as is customarily used in the microscopic methods just described. Samples used for particle size determination would have to be diluted immediately after passing through the orifices, in order to retard coagulation while observations were being made.

3. Character of Floc:

The data obtained in this investigation on the effects of aging, concentration, and ionic strength suffice to show that these factors are important in the removal process. Further supporting data are necessary to determine the quantitative significance of each. The effect of hydrogen ion concentration has been roughly determined but more data is required in order to substantiate that plotted in Figure 7.

4. Removal Mechanisms:

Sufficient fundamental information is not available on the relative importance of the different processes involved in the removal of suspended particles, by a sand filter. In lieu of a thorough study, observations of the gross process under different conditions will have to suffice. An indication of the importance of sedimentation in the removal process might be obtained by noting the effect, if any, of operating a filter in the horizontal, instead of in the usual vertical position. With horizontal flow, the force of gravity would be at right angles to the mean direction of flow but in vertically downward flow, this force would be in the same direction. Experiments in which the size of floc particles is varied should supply data of value for determining the relative importance of the different removal mechanisms. If flocculation within the pores of a filter is important in the removal process, its effect could readily be determined by using a very dilute suspension of floc. In a dilute suspension, flocculation would be greatly reduced and its effect therefore might be possible to assess.

5. Porosity of Bed, Sand Shape and Size Distribution:

The author's experiments were conducted with sand beds of substantially uniform porosity, sand shape, and size. In practice, these factors might all vary, depending on local conditions. Therefore, it is necessary to investigate their importance in order to apply the experimental results to practice.

6. Coagulants:

The experiments were conducted with only one type of coagulant: $FeCl_3$. The general applicability of the results should be investigated by conducting experiments with different coagulants.

ACKNOWLEDGMENTS

This paper is based on material obtained from a thesis presented by the author in partial fulfillment of the requirements for the Degree of Doctor of Science, Graduate School of Arts and Sciences, Harvard University. The author is indebted to Professors G.M. Fair and H.A. Thomas, Jr., and the other faculty members of the Department of Sanitary Engineering, Harvard University for their guidance in the preparation of the thesis.

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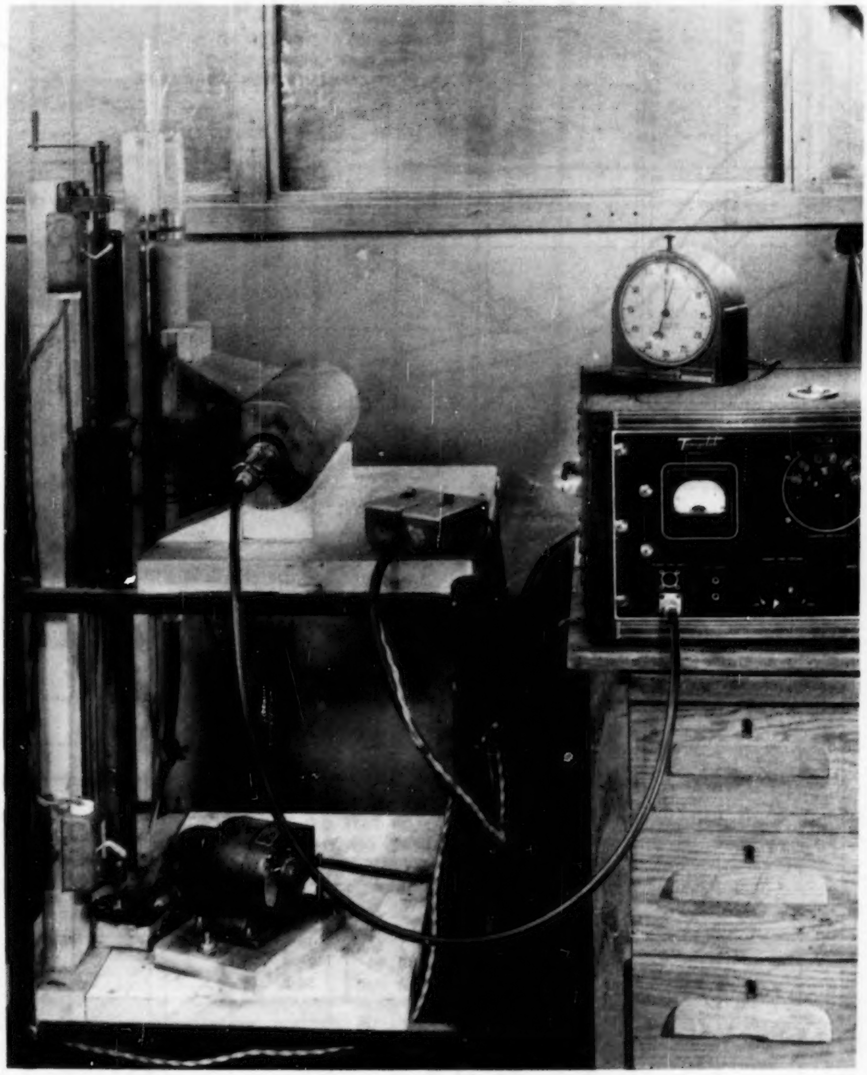

Figure I

COUNTING EQUIPMENT WITH FILTER ASSEMBLY IN PLACE

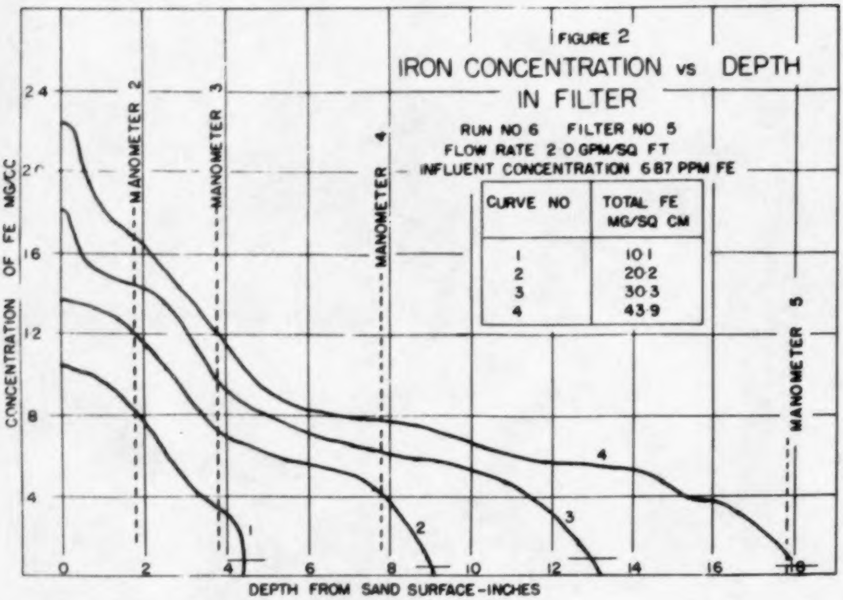
FIGURE 2
IRON CONCENTRATION vs DEPTH IN FILTER
RUN NO 6 FILTER NO 5
FLOW RATE 2 0 GPM/SQ FT
INFLUENT CONCENTRATION 6 87 PPM FE
CURVE NO | TOTAL FE MG/SQ CM
1 | 10 1
2 | 20 2
3 | 30 3
4 | 43 9
MANOMETER 2
MANOMETER 3
MANOMETER 4
MANOMETER 5
CONCENTRATION OF FE MG/CC
DEPTH FROM SAND SURFACE-INCHES

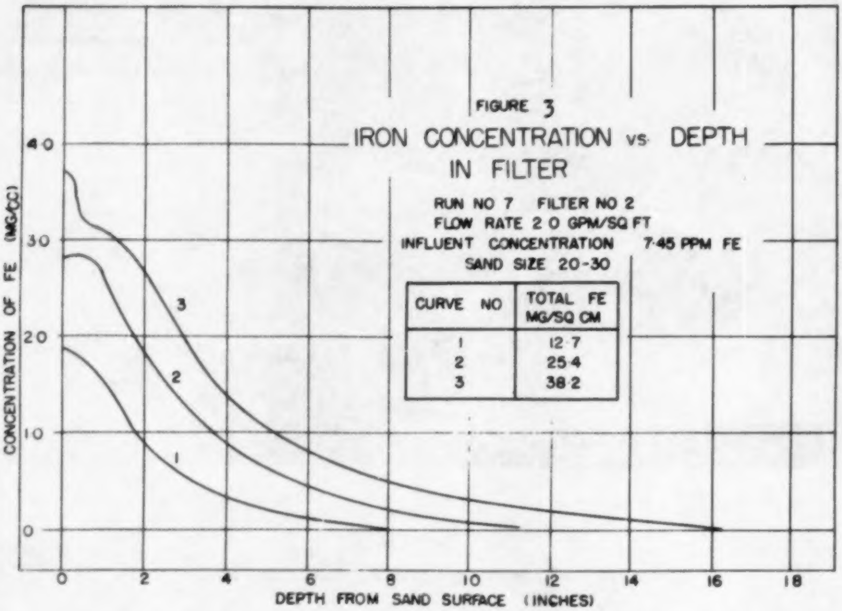
FIGURE 3
IRON CONCENTRATION vs DEPTH IN FILTER
RUN NO 7 FILTER NO 2
FLOW RATE 2 0 GPM/SQ FT
INFLUENT CONCENTRATION 7 45 PPM FE
SAND SIZE 20-30
CURVE NO | TOTAL FE MG/SQ CM
1 | 12 7
2 | 25 4
3 | 38 2
CONCENTRATION OF FE (MG/CC)
DEPTH FROM SAND SURFACE (INCHES)

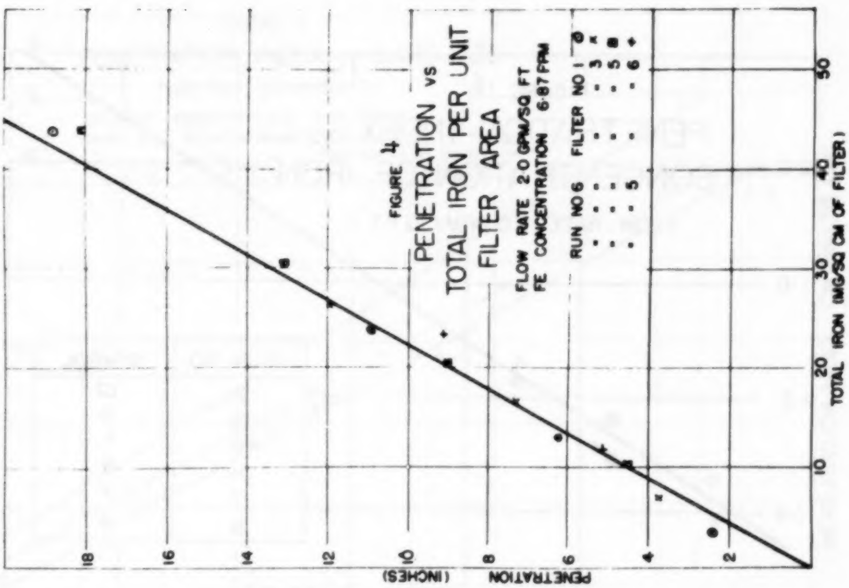
FIGURE 4
PENETRATION vs
TOTAL IRON PER UNIT
FILTER AREA
FLOW RATE 2.0 GPM/SQ FT
FE CONCENTRATION 6.87 PPM
RUN NO 6 FILTER NO 1
" " " " " 3
" " 5 " " 5
" " " " " 6
PENETRATION (INCHES)
TOTAL IRON (MG/SQ CM OF FILTER)

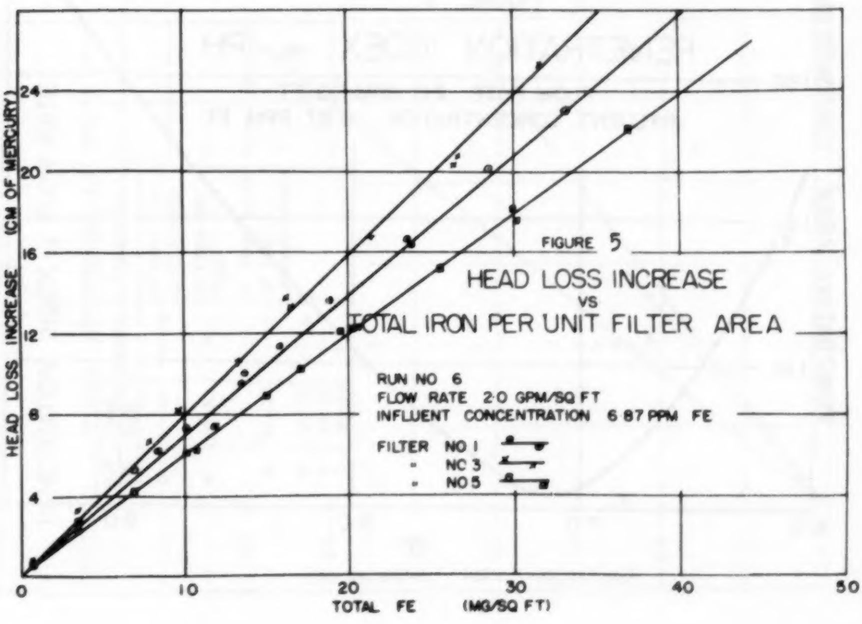
FIGURE 5
HEAD LOSS INCREASE
VS
TOTAL IRON PER UNIT FILTER AREA
RUN NO 6
FLOW RATE 2.0 GPM/SQ FT
INFLUENT CONCENTRATION 6.87 PPM FE
FILTER NO 1
" NO 3
" NO 5
HEAD LOSS INCREASE (CM OF MERCURY)
TOTAL FE (MG/SQ FT)

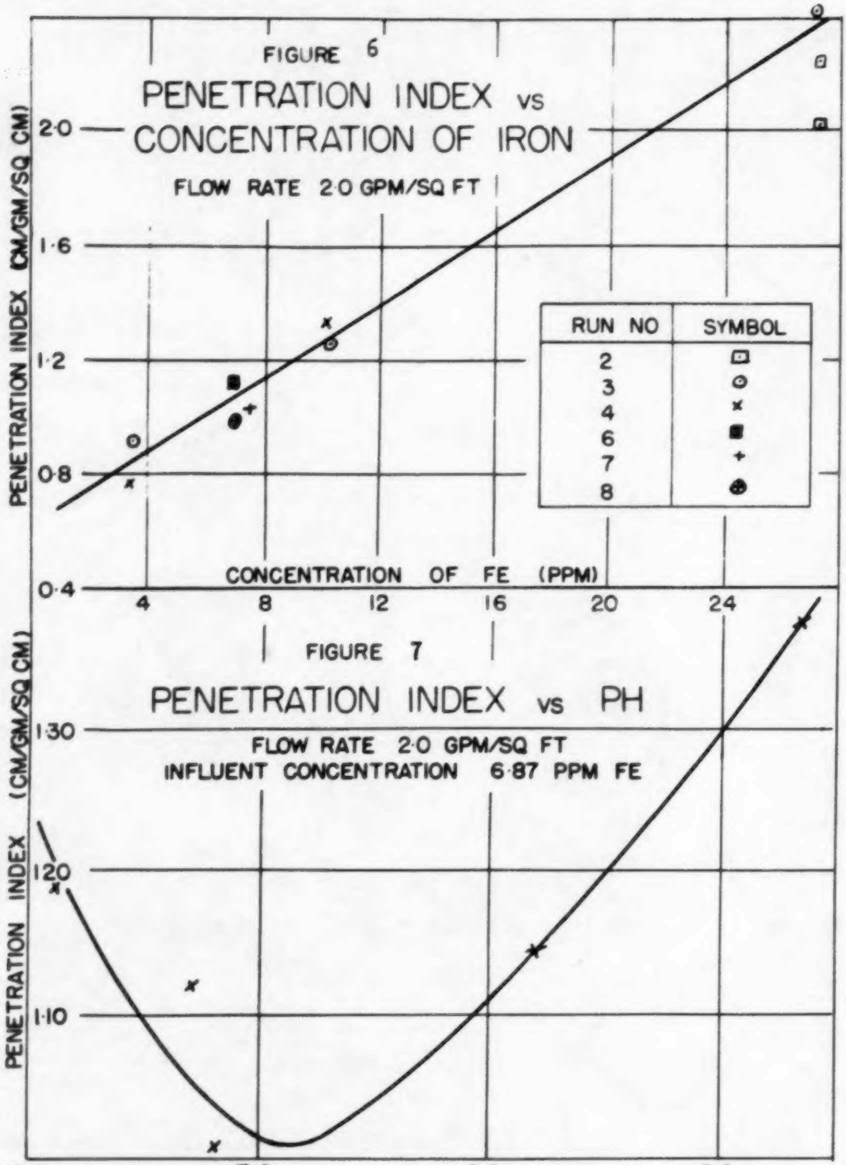
FIGURE 6
PENETRATION INDEX vs CONCENTRATION OF IRON
FLOW RATE 2.0 GPM/SQ FT
PENETRATION INDEX (CM/GM/SQ CM)
2.0
1.6
1.2
0.8
0.4
RUN NO
SYMBOL
2
3
4
6
7
8
CONCENTRATION OF FE (PPM)
4
8
12
16
20
24
FIGURE 7
PENETRATION INDEX vs PH
FLOW RATE 2.0 GPM/SQ FT
INFLUENT CONCENTRATION 6.87 PPM FE
PENETRATION INDEX (CM/GM/SQ CM)
1.30
1.20
1.10
6.0
7.0
8.0
9.0
PH

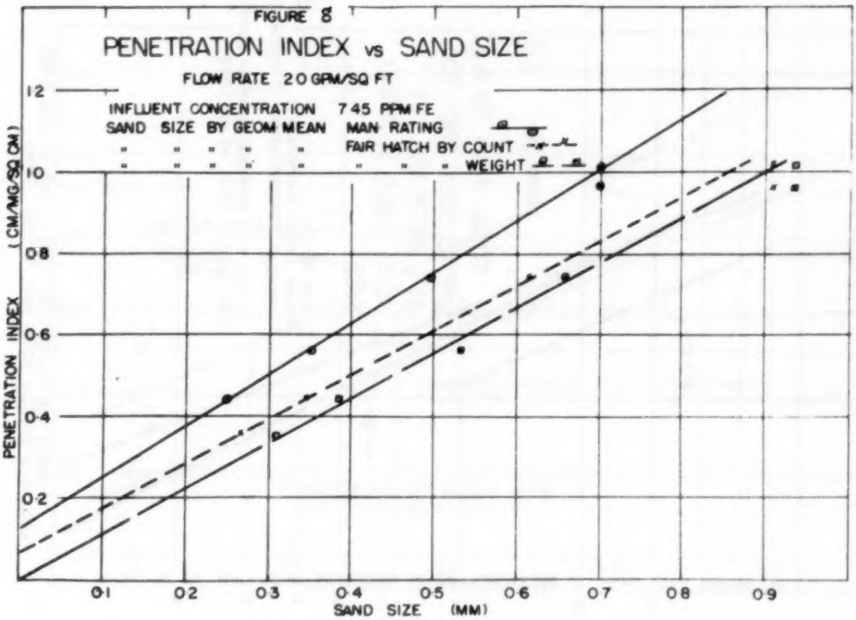
FIGURE 8
PENETRATION INDEX vs SAND SIZE
FLOW RATE 2.0 GPM/SQ FT
INFLUENT CONCENTRATION 7.45 PPM FE
SAND SIZE BY GEOM MEAN MAN RATING
FAIR HATCH BY COUNT
WEIGHT
PENETRATION INDEX (CM/MG/SQ CM)
SAND SIZE (MM)
1.2
1.0
0.8
0.6
0.4
0.2
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

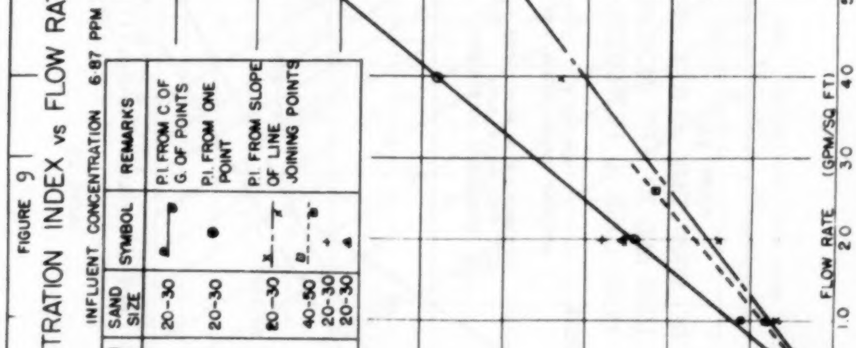
FIGURE 9
PENETRATION INDEX vs FLOW RATE
INFLUENT CONCENTRATION 6.87 PPM FE
RUN NO
SAND SIZE
SYMBOL
REMARKS
8
20-30
P.I. FROM C. OF G. OF POINTS
8
20-30
P.I. FROM ONE POINT
8
20-30
P.I. FROM SLOPE OF LINE JOINING POINTS
8
40-50
6
20-30
7
20-30
PENETRATION INDEX (CM/MG/SQ CM)
FLOW RATE (GPM/SQ FT)
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0
1.0
2.0
3.0
4.0
5.0

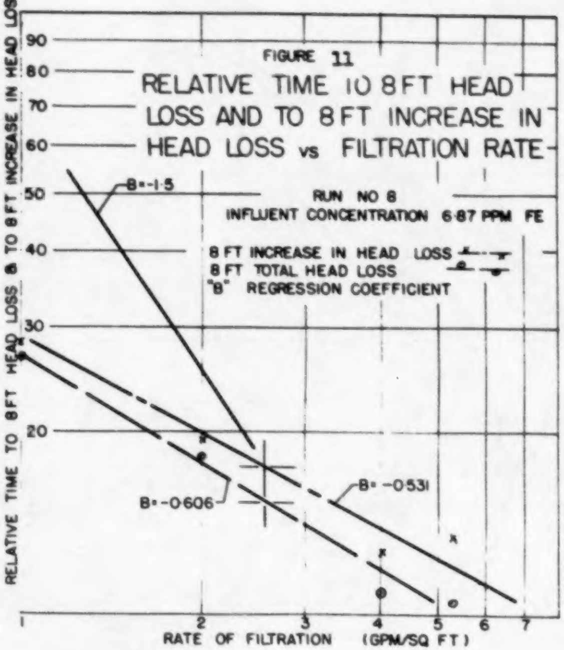
FIGURE 11
RELATIVE TIME IO 8 FT HEAD LOSS AND TO 8 FT INCREASE IN HEAD LOSS vs FILTRATION RATE
RUN NO 8
INFLUENT CONCENTRATION 6·87 PPM FE
8 FT INCREASE IN HEAD LOSS
8 FT TOTAL HEAD LOSS
"B" REGRESSION COEFFICIENT
B=-1·5
B=-0·606
B=-0·531
RELATIVE TIME TO 8 FT HEAD LOSS & TO 8 FT INCREASE IN HEAD LOSS
RATE OF FILTRATION (GPM/SQ FT)
90
80
70
60
50
40
30
20
1
2
3
4
5
6
7

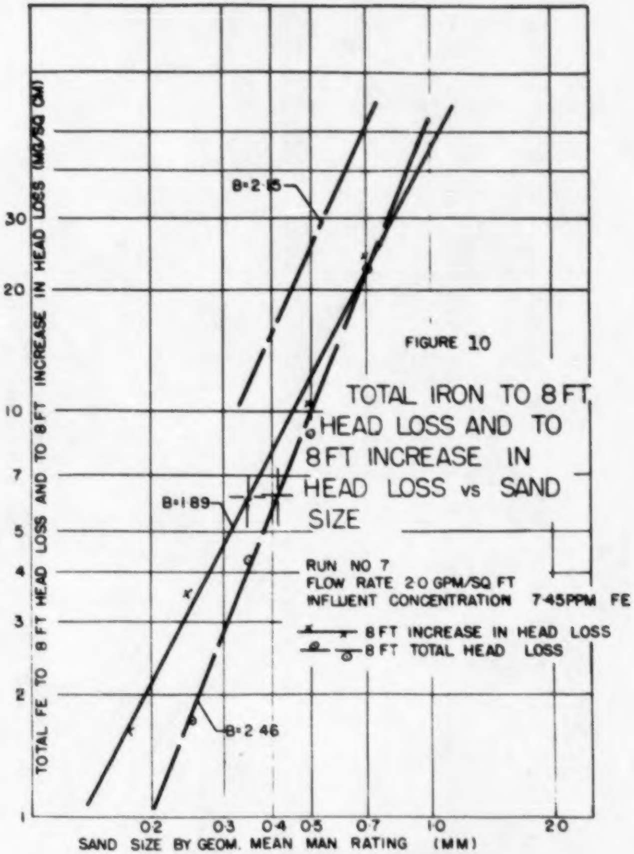
FIGURE 10
TOTAL IRON TO 8 FT HEAD LOSS AND TO 8 FT INCREASE IN HEAD LOSS vs SAND SIZE
RUN NO 7
FLOW RATE 2·0 GPM/SQ FT
INFLUENT CONCENTRATION 7·45 PPM FE
8 FT INCREASE IN HEAD LOSS
8 FT TOTAL HEAD LOSS
B=2·85
B=1·89
B=2·46
TOTAL FE TO 8 FT HEAD LOSS AND TO 8 FT INCREASE IN HEAD LOSS (MG/SQ CM)
SAND SIZE BY GEOM. MEAN MAN RATING (MM)
30
20
10
7
5
4
3
2
1
0·2
0·3
0·4
0·5
0·7
1·0
2·0

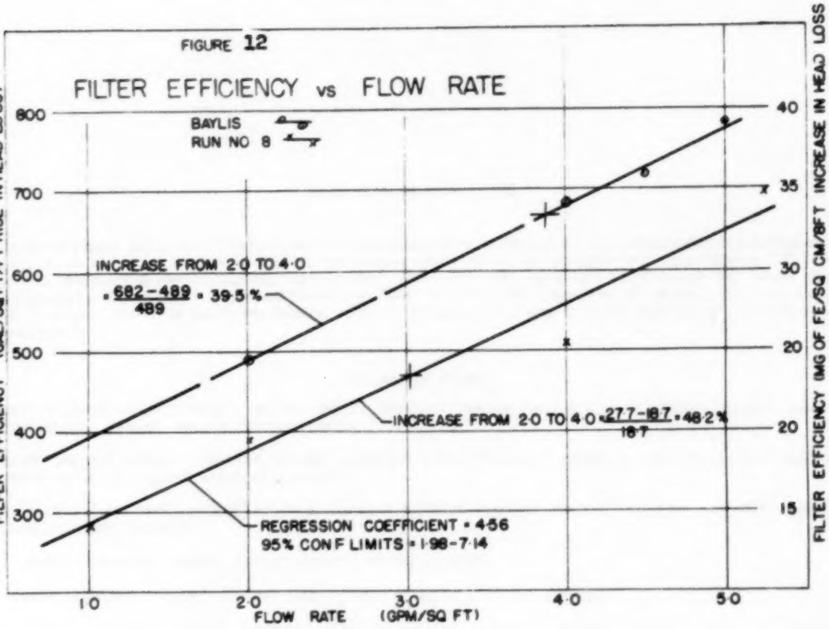
FIGURE 12
FILTER EFFICIENCY vs FLOW RATE
BAYLIS
RUN NO 8
INCREASE FROM 2·0 TO 4·0
= 682 − 489 / 489 = 39·5 %
INCREASE FROM 2·0 TO 4·0 = 27·7 − 18·7 / 18·7 = 48·2 %
REGRESSION COEFFICIENT = 4·56
95% CONF LIMITS = 1·98 − 7·14
FILTER EFFICIENCY (GAL/SQ FT/FT RISE IN HEAD LOSS)
FILTER EFFICIENCY (MG OF FE/SQ CM/BFT INCREASE IN HEAD LOSS)
FLOW RATE (GPM/SQ FT)
800
700
600
500
400
300
40
35
30
20
20
15
1·0
2·0
3·0
4·0
5·0

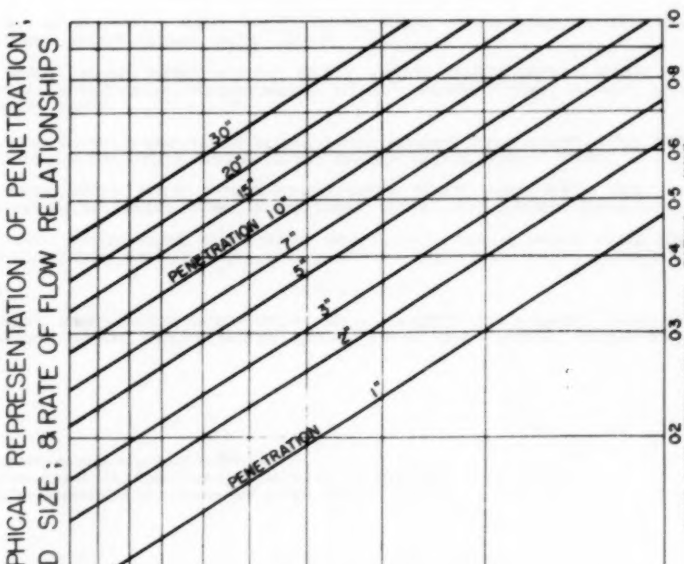
FIGURE 13
GRAPHICAL REPRESENTATION OF PENETRATION; SAND SIZE; & RATE OF FLOW RELATIONSHIPS
30"
20"
15"
PENETRATION 10"
7"
5"
3"
2"
PENETRATION 1"
SAND SIZE GEOM MEAN, MAN. RATING (MM)
RATE OF FLOW (GPM/SQ FT)
0·1
0·2
0·3
0·4
0·5
0·6
0·8
1·0
8
7
6
5
4
3
2

PROCEEDINGS-SEPARATES

The technical papers published in the past year are presented below. Technical-division sponsorship is indicated by an abbreviation at the end of each Separate Number, the symbols referring to: Air Transport (AT), City Planning (CP), Construction (CO), Engineering Mechanics (EM), Highway (HW), Hydraulics (HY), Irrigation and Drainage (IR), Power (PO), Sanitary Engineering (SA), Soil Mechanics and Foundations (SM), Structural (ST), Surveying and Mapping (SU), and Waterways (WW) divisions. For titles and order coupons, refer to the appropriate issue of "Civil Engineering" or write for a cumulative price list.

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FEBRUARY: 398(IR)[d], 399(SA)[d], 400(CO)[d], 401(SM)[c], 402(AT)[d], 403(AT)[d], 404(IR)[d], 405(PO)[d], 406(AT)[d], 407(SU)[d], 408(SU)[d], 409(WW)[d], 410(AT)[d], 411(SA)[d], 412(PO)[d], 413(HY)[d].

MARCH: 414(WW)[d], 415(SU)[d], 416(SM)[d], 417(SM)[d], 418(AT)[d], 419(SA)[d], 420(SA)[d], 421(AT)[d], 422(SA)[d], 423(CP)[d], 424(AT)[d], 425(SM)[d], 426(IR)[d], 427(WW)[d].

APRIL: 428(HY)[c], 429(EM)[c], 430(ST), 431(HY), 432(HY), 433(HY), 434(ST).

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JUNE: 444(SM)[e], 445(SM)[e], 446(ST)[e], 447(ST)[e], 448(ST)[e], 449(ST)[e], 450(ST)[e], 451(ST)[e], 452(SA)[e], 453(SA)[e], 454(SA)[e], 455(SA)[e], 456(SM)[e].

JULY: 457(AT), 458(AT), 459(AT)[c], 460(IR), 461(IR), 462(IR), 463(IR)[c], 464(PO), 465(PO)[c].

AUGUST: 466(HY), 467(HY), 468(ST), 469(ST), 470(ST), 471(SA), 472(SA), 473(SA), 474(SA), 475(SM), 476(SM), 477(SM), 478(SM)[c], 479(HY)[c], 480(ST)[c], 481(SA)[c], 482(HY), 483(HY).

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c. Discussion of several papers, grouped by Divisions.

d. Presented at the Atlanta (Ga.) Convention of the Society in February, 1954.

e. Presented at the Atlantic City (N.J.) Convention in June, 1954.

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